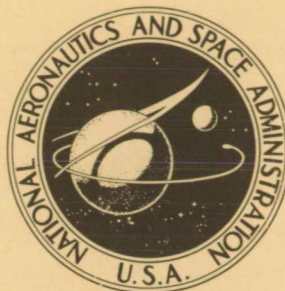


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A STUDY OF TOTAL SPACE LIFE PERFORMANCE OF GSFC SPACECRAFT

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16. Abstract The study covers the total space life performance of 57 Goddard Space Flight Center spacecraft. It is a sequel to two previous studies (first-day and first-month space performance) of the same 57 spacecraft. The time distribution of 449 malfunctions, of which 248 were classified as failures, is presented. Test data were available for 39 of the spacecraft and permitted a comparison of system test performance with the first-day, first-month, and total space life performance. The failures per spacecraft for the system environmental tests and the three time periods in space were 12, 0.9, 1.7, and 5.0, respectively. Relevance of the data to the pre-Shuttle and Shuttle eras is discussed. Classifications of failures by type of device and spacecraft subsystem are included. A continuation of the Goddard philosophy of requiring a system-level environmental test program is justified.					
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A STUDY OF TOTAL SPACE LIFE PERFORMANCE OF GSFC SPACECRAFT

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INTRODUCTION

The space performance of an unmanned spacecraft has many aspects which are of differing importance to different user groups. For instance, the communications user groups are interested in long life and reliable operations. On the other hand, an experimenter may be interested in a few days of operation but at a precise time. Other experiments may need to be exposed to a range of space environments to verify readiness for an operational type of application.

The space experience of a single spacecraft is useful to any user group in assessing the value of the test program associated with the spacecraft. The space experience of many spacecraft, however, is of greater value, and to a larger group that includes top management, project managers, designers, budget analysts, program planners, test and evaluation personnel, and reliability assurance functions. To fulfill this need for grouped space experience, the performance of 57 Goddard Space Flight Center (GSFC) spacecraft has been used. The present study emphasizes the total space life performance of the spacecraft. However, the study complements two previous studies (references 1 and 2) which documented the first-day and the first-month space performance of the same 57 spacecraft. The data base has been maintained constant where possible to facilitate the use of all three reports for a given need or purpose. However, the data in this report should be used if any differences are observed between this report and the two previous reports. For instance, additional documented first-day malfunctions which were received subsequent to the publication of reference 1 have been included in this report.

DATA BASE

The data for this study are taken from the performance of 57-unmanned spacecraft developed under the management of GSFC. The spacecraft include:

- Four meteorological spacecraft
- Two astronomical observatories
- Six geophysical observatories
- Six solar observatories

- Six applications technology spacecraft
- Seven interplanetary monitoring platforms
- Twelve operational weather spacecraft
- Fourteen miscellaneous scientific missions

The experiments and subsystems for these spacecraft have been provided by various organizations, including GSFC, other government agencies, universities, and aerospace companies. Eighteen of the spacecraft received a full system test at GSFC, and the remaining 39 received a full system test in a contractor's facility.

Throughout the report, the terms failure and malfunction will be encountered, and an understanding of the difference between them is necessary. The following definitions will be applicable:

- A malfunction is any performance outside the specified limits and can be either a failure or a problem.
- A failure is the loss of operation of any function, part, component, or subsystem, whether or not redundancy permitted a recovery of operation.
- A problem is any substandard performance or partial loss of function which is not sufficient to be classed as a failure.

TIME DISTRIBUTION OF SPACE MALFUNCTIONS

Figure 1 shows the time distribution (in 30-day increments) of the malfunctions and failures documented for the 57 GSFC spacecraft. Figure 2 presents the space malfunctions (and, separately, the space failures) in a cumulative fashion for the first 3 years in space. Figure 3 shows the number of spacecraft that were still alive for each of the 30-day time increments up to 1080 days. This figure also shows that the unnormalized data of figures 1 and 2 must be regarded as minimum values; for instance, after one year, the number of spacecraft contributing to the data base has been reduced from 57 to 43. Figure 4 is another cumulative presentation showing the percent of total space failures for each 30 days of space life up to 1080 days.

CLASSIFICATIONS OF SPACE MALFUNCTIONS

A classification, by type of device, of the space malfunctions from the 57 spacecraft is given in table 1. The percentage of malfunctions ascribed to electrical-type devices constitutes over 50 percent of the total malfunctions for each of the three time periods (first day, first month, and total space life).

Another classification, by spacecraft function, of the malfunctions from the 57 spacecraft is given in table 2. The experiments comprise approximately 50 percent of the malfunctions for each of the three time periods shown. The command and data handling function is the

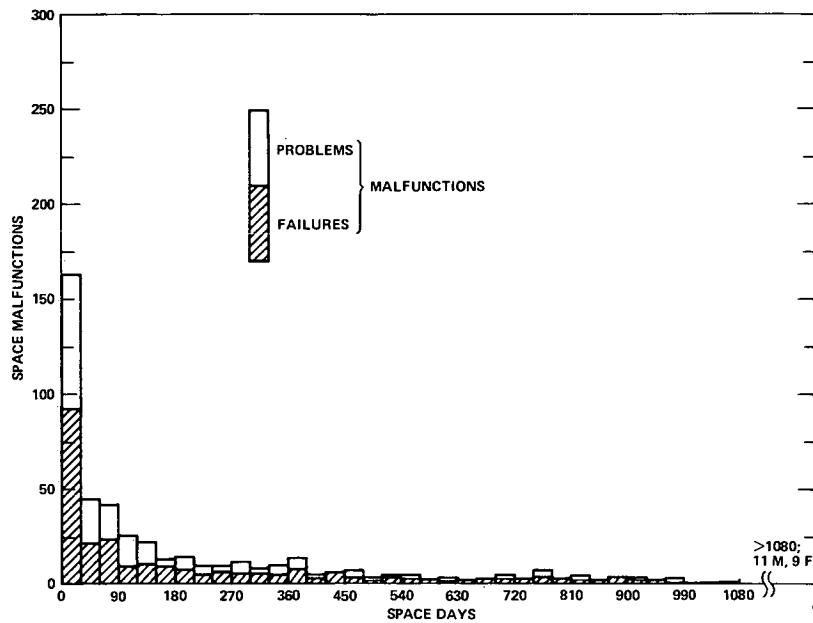


Figure 1. Time distribution of space malfunctions from 57 GSFC spacecraft.

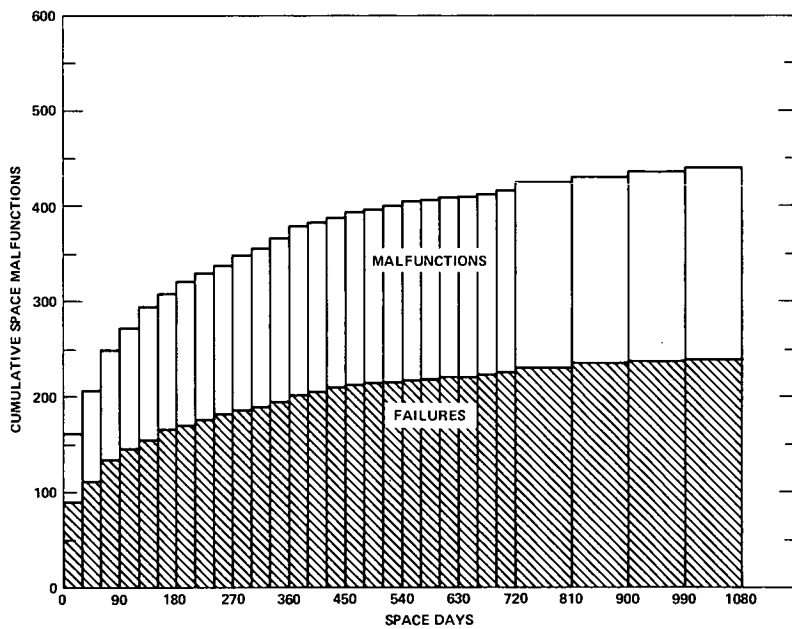


Figure 2. Relationship of space malfunctions and time.

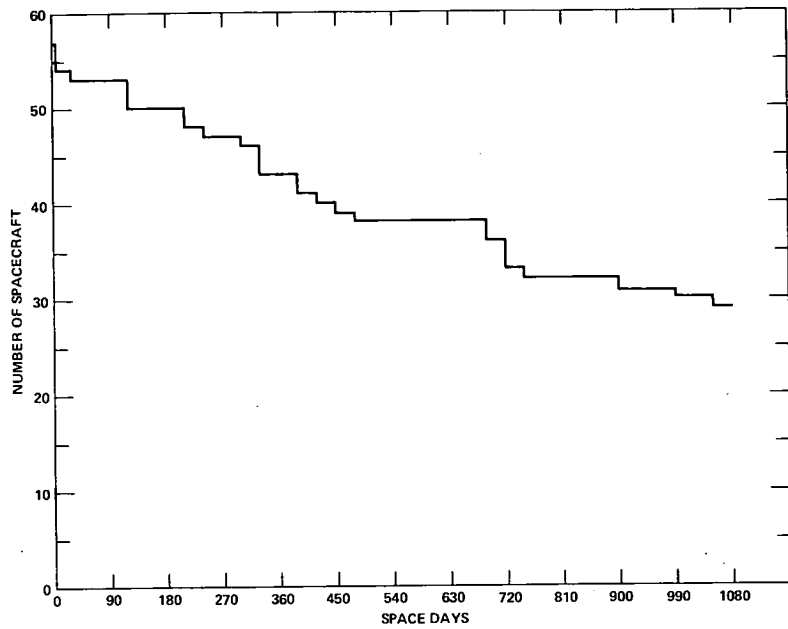


Figure 3. Distribution of space lives of 57 GSFC spacecraft.

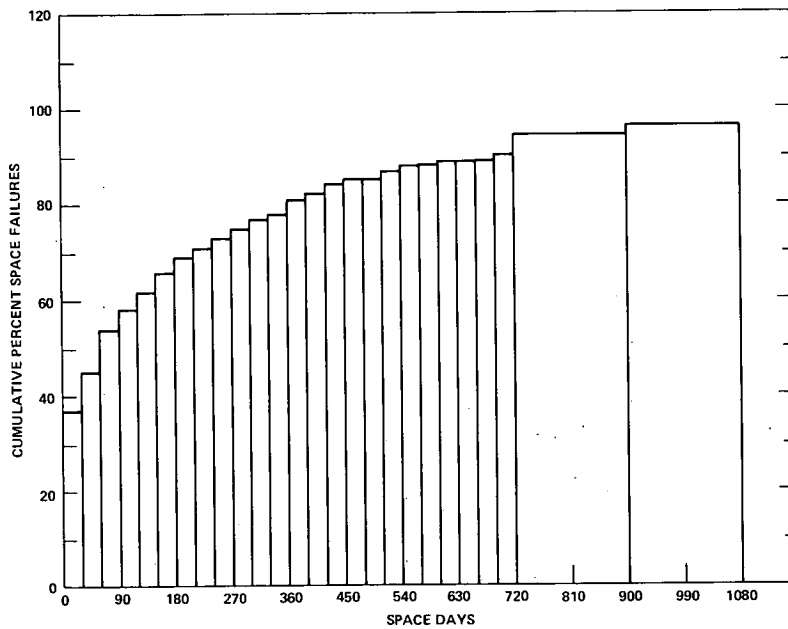


Figure 4. Percent of space failures versus time for 57 GSFC spacecraft.

Table 1
Classification of Space Malfunctions from 57 Spacecraft by Type of Device

Type of Device	Percent Space Malfunctions		
	First Day	First Month	Total Space
Electrical	57	59	57
Electromechanical	17	21	12
Mechanical	16	12	16
Miscellaneous	10	8	15
	<u>100</u>	<u>100</u>	<u>100</u>

Table 2
Classification of Space Malfunctions from 57 Spacecraft by Spacecraft Function

Spacecraft Function	Percent Space Malfunctions		
	First Day	First Month	Total Space
Experiment	48	47	50
Command and Data Handling	16	20	25
Stabilization and Control	10	14	13
Power	9	9	8
Other	17	10	4
	<u>100</u>	<u>100</u>	<u>100</u>

next largest contributor to the space malfunctions, and its percentage contribution increases for each of the three time periods.

LIMITATIONS ON DATA

The data base for this report is considered to be comprehensive and representative. Nevertheless, some limitations need to be kept in mind when assessing or using the results. The data are necessarily based on reported malfunctions. Some differences between reported and actual malfunctions can be expected, based on the wide spectrum of individuals responsible for reporting a malfunction. Although there is no way to quantify the difference, it is thought to be small. For instance, the number of documented first-day space malfunctions for the spacecraft of this study has increased about 15 percent since reference 1 was published in 1971. This situation emphasizes the fact that the malfunction data should be considered a minimum.

The problem of radio frequency interference, including spurious commands, has been purposely omitted from this study. This specialized problem has varied widely between satellites, orbits, location and power of ground-based energy sources, and command systems. The omission is indicative of the importance rather than unimportance of this type of malfunction. For instance, an early spacecraft had 400 anomalous command states during the first year in space. Inclusion of such data would have obscured the findings of this study. Because of continuing problems in this field, radio frequency interference testing of spacecraft before launch is considered as important now, if not more so, than in the early days of the space program.

Ground station problems are another category which has not been included in this study. In the main, these are temporary, equipment-related, personnel-related types of events. When a malfunction was definitely ascribed to a spacecraft, it was then included as part of this study.

CRITICALITY OF MALFUNCTIONS

The 449 malfunctions on the 57 spacecraft include items of differing importance or criticality and also include critical malfunctions which were not serious because redundancy permitted complete fulfillment of the desired function. Another aspect of criticality is that the effect of the malfunction on the mission can be completely different than the effect on the component. To aid in the discussion of criticality, two terms are defined:

- Mission criticality—A measure of the effect of a malfunction on the achievement of the mission objectives. The loss is given as a percentage of the mission objectives.
- Component criticality—A measure of the effect of a malfunction on the operation of a component. The loss is given as a percentage of component operation.

Mission and component criticality can each be considered with and without redundancy. Figure 5 gives some perspective on the distribution of the malfunctions with respect to mission criticality. Seventy-three percent of the malfunctions are classified as minor loss to the mission, assuming no redundancy, and 27 percent are classified as substantial or greater loss. With actual redundancy, the malfunctions classified as minor loss to mission were 85 percent, and 15 percent were classified as substantial or greater loss. Another aspect of the benefit gained from redundancy is that the benefit extended to each of the three significant classifications (catastrophic, major, and substantial).

Figure 5 also shows the component criticality distribution of malfunctions. The distribution, which assumes no redundancy existed, shows that the majority (55 percent) of the malfunctions were significant. Further, about 35 percent of the malfunctions were catastrophic loss of components. The criticality distribution of malfunctions, which shows the effect of actual redundancy, indicates that redundancy has effectively reduced the percentage of significant malfunctions from 55 to 36 percent. Figure 5 further shows that the percentage of catastrophic failures of components has been reduced from 35 to 23 percent through the benefits of redundancy.

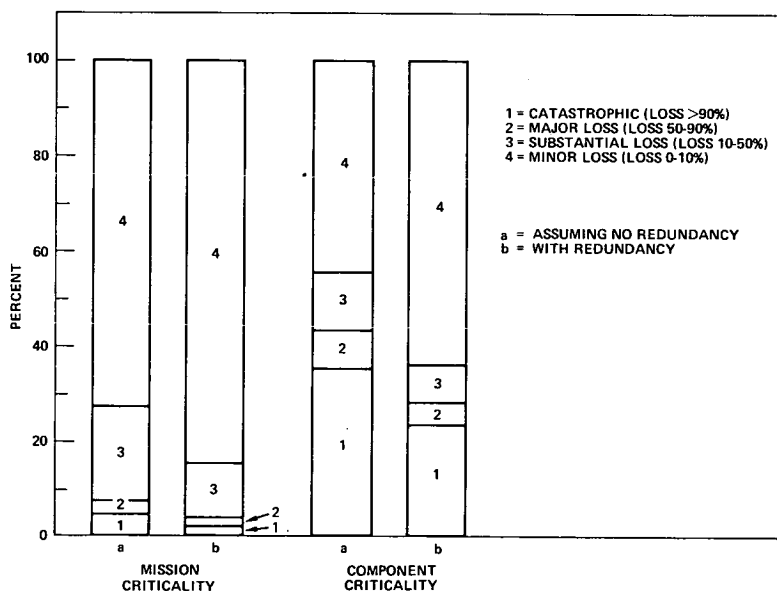


Figure 5. Criticality of total space malfunctions of 57 GSFC spacecraft.

OBSERVATIONS

The time distributions of the space malfunctions from the spacecraft are given in 30-day increments in figures 1, 2, and 4. Figure 3 shows that all of the 57 spacecraft did not

operate for the entire 3-year time period covered. These data indicate several important points, as follows:

- The comparatively large number of malfunctions in the first 30 days in space shows that all of the infant mortality type of malfunctions were not eliminated prior to launch. To further assess the first 30-day performance, reference 2 is recommended. It contains both mission and component criticality data together with other analyses of the data.
- If there is a constant failure rate region, it does not occur until 90 (or probably more) days in space. Therefore, the exponential relationship for describing reliability in space is not considered appropriate because it is based upon a constant failure rate.
- There is no indication of a wear-out phase of spacecraft components over the 3 years of space life covered by these data. This is reassuring from the standpoint of life expectancy in space. Although individual spacecraft have had remarkable lifetimes in space (for instance, useful data were obtained from one GSFC spacecraft for over 8 years), summarized data on many spacecraft have not been reported. The composite data from this study indicate that long life is achievable for most spacecraft.
- The data from figures 1 and 2 must be regarded as minimum values because of the decreasing sample size with time. (This is in addition to the question of completeness of reported malfunctions mentioned previously.)
- A safe estimate of the ratio of problems to failures is one-to-one. The ratio can be used for gross estimates of malfunctions if only failure data are available for various time periods in total space life. For more meaningful assessments, these data must be coupled with the component and mission criticality data.
- The data need to be normalized to make them more usable for estimating purposes.

Figures 6, 7, and 8 are normalized data. Figure 6 gives the malfunctions (and, separately, the failures) per spacecraft in 30-day increments for the first 1.5 years in space and in 60-day increments for the second 1.5 years in space. The data are in more usable form than the raw data of figure 1 and furnish a basis for estimating space performance based on past experience. Figure 7 gives the same data but on a cumulative basis. Normalizing the data has not changed the characteristic shape of the raw data from figure 2 but again makes the data more usable. Using this figure, the best estimates of expected failures for a spacecraft for 30 days and for 3 years in space would be 1.7 and 5, respectively. Similar estimates can be made for the number of malfunctions and for other time periods. Figure 8 (similar to figure 4 but using normalized data) shows the percent of the total space failures that can be expected in 30-day time increments for the 3 years covered by the data. As can be seen from the figure, the percentages for 30, 180, and 360 days are 34, 62, and 75 percent,

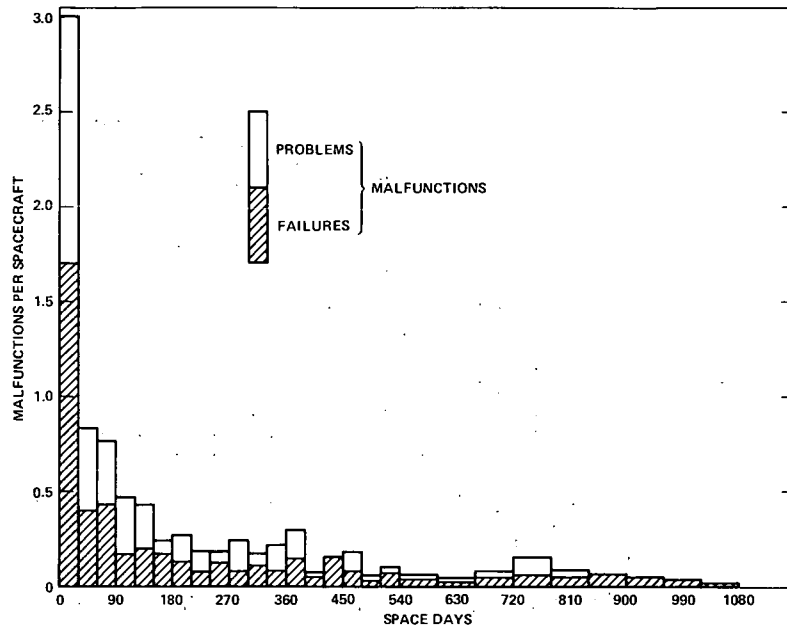


Figure 6. Time distribution of normalized space malfunctions from 57 GSFC spacecraft.

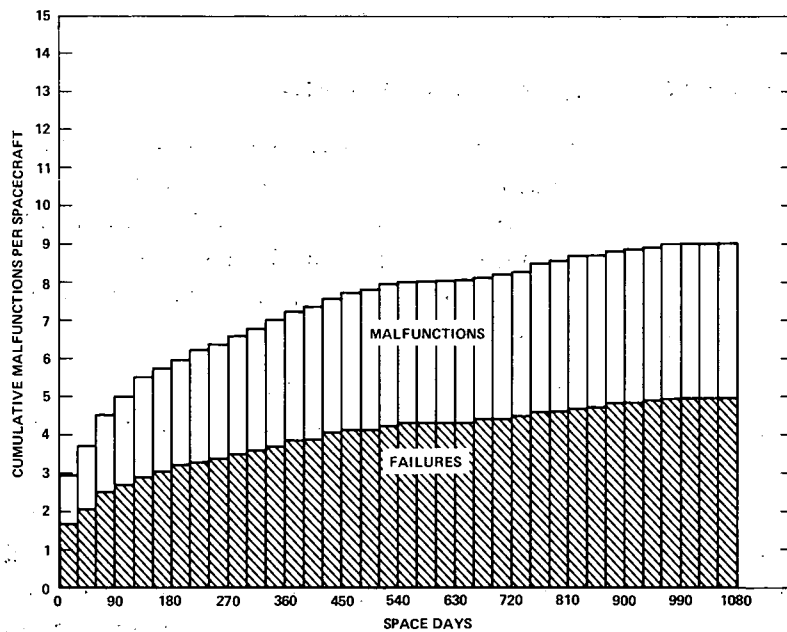


Figure 7. Normalized space malfunctions related to time.

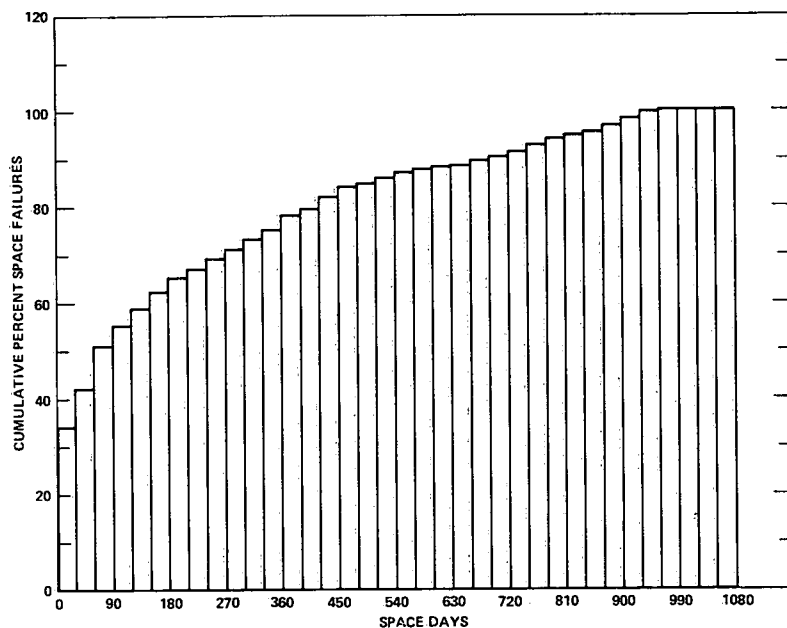


Figure 8. Percent of normalized space failures versus time.

respectively. A separate graph was not prepared for malfunctions (problems plus failures) because the results were almost identical to figure 8.

RELEVANCE OF DATA TO THE PRE-SHUTTLE ERA

With the decrease in available funds in the past few years and possible additional cuts in the future, the emphasis has been on cutting costs even if it resulted in entailing additional risk. Taking additional risk without data could be expected to lead to a catastrophe. The data from the present study will not permit precise quantification of risk, but they should be helpful in assessing the role of system-level testing of spacecraft and in estimating the effect of major changes in system test programs.

The time distribution of normalized space malfunctions is shown in figure 6. It shows 1.7 failures per spacecraft and 3.0 malfunctions per spacecraft for the first 30 days in space. Each of the 57 spacecraft had a system-level environmental test program prior to launch.

What would the space performance have been if there had been no system-level tests? A useful answer can be gained by making the following assumption: All the system-level malfunctions occurred in a 30-day period, and, if they had not been corrected, they would have occurred in the first 30 days in space. This assumption overstates the case, primarily because all the system-level failures were not environmentally induced and some would be detected with a thorough functional checkout. On the other hand, all of the actual space

malfunctions were deferred by one 30-day time increment as part of the assumption. Thus, some unknown number of actual 30-day space malfunctions may now be excluded. Overall, the assumption is considered to lead to an upper boundary on expected space failures.

The assumption, therefore, provides a means for useful and relevant insight to the space performance to be expected if system-level environmental tests had been eliminated on the spacecraft of this study. Using this assumption, figure 9 was constructed; it shows 12 failures per spacecraft for the system tests. (Malfunctions per spacecraft, not shown in figure 9, were 27.) This indicates that a sevenfold increase in failures (and ninefold increase for malfunctions) for the first 30 days in space would have resulted if system-level environmental tests had not been conducted on the spacecraft. In other words, there would have been about 1500 malfunctions, of which approximately 680 would have been classified as failures for the first 30 days in space. Table 3 summarizes these and other data.

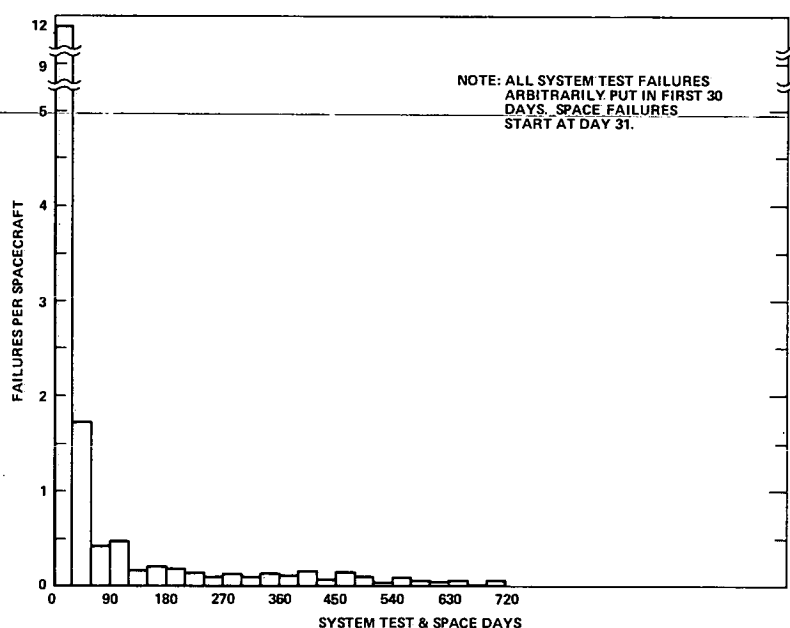


Figure 9. Time distribution of system test plus space failures of 57 GSFC spacecraft.

Another interesting question concerns the percentage of total space malfunctions that occur in the first 30 days in space. How much change in the percentage might be expected if no system-level environmental test program were conducted? Figure 8 shows that 34 percent of the total space malfunctions from the 57 spacecraft occurred in the first 30 days.

Table 3 shows that 75 percent of the total space malfunctions may occur in the first 30 days if system-level environmental tests are completely eliminated. Table 3 also shows that

Table 3
Potential Effect of No System-Level Tests on Space Performance of 57 GSFC Spacecraft

Item Affected	Per Spacecraft		Total Number	
	Failures	Malfunctions	Failures	Malfunctions
Actual Normalized Data for 57 Spacecraft				
System Tests*	12	26.8	684	1528
Thirty Days in Space	1.7	3.0	97	171
Total Space Life	5.0	9.0	285	513
Percent in First 30 Space Days	34	33	34	33
Projected Space Performance Without System-Level Tests†				
Thirty Days in Space	12	26.8	684	1528
Total Space Life	17	35.8	969	2041
Percent in First 30 Space Days	70	75	70	75

* System test data, available on 39 spacecraft, was normalized to 57 spacecraft.

† See text for assumption.

75 percent of the total space malfunctions amounts to over 1500 malfunctions for the 57 spacecraft. This would have a significant effect on mission success if the best estimates of criticality of first-month space malfunctions from reference 2 are used. Those estimates for mission criticality, after making allowance for the benefit of redundancy, are 2 percent for catastrophic losses and 14 percent for all significant losses. By combining these values of criticality with the 1528 malfunctions (see table 3) from the 30 days of system tests, an estimate of mission-critical losses can be made. An estimate of the number of catastrophic losses would be about 30, and for all significant mission malfunctions, about 229. Clearly, such space performance would be unacceptable. Even if the assumption of the number of system-level malfunctions was decreased by 50 percent, the space performance would still be unacceptable. A goal in the pre-Shuttle era should be to demonstrate that the hardware quality has, or can be, improved, compared to that represented by this study. These results lead to two important points with respect to the pre-Shuttle era:

- A study is necessary to show if the system test and space performance have changed since 1970 (present study covered 1960 to 1970).
- Until results are available to discount the data of the present study, the GSFC philosophy of requiring system-level tests of flight spacecraft is not only justified but necessary to maintain a satisfactory space performance.

RELEVANCE OF DATA TO THE SHUTTLE ERA

Extensive studies have been conducted on the Shuttle concept and on the low cost payload aspect of it. Some generalized aspects envision standardized, modularized hardware, which in itself would result in large cost savings, and a reduction or possible elimination of the need for system-level environmental tests could result in additional savings. The inference of the present study is that these tenets should be demonstrated before the Shuttle era.

With no change in hardware quality or test requirements, the results of this study indicate that, for the first 30 days in space, three malfunctions per spacecraft (with about half of these classified as failures) can be expected. Without system-level environmental tests (and with no change in hardware quality), the expectation would be 27 malfunctions per spacecraft, of which 12 would be failures for the first 30 days in space.

To arrive at the desired cost-effective status envisioned by the cost studies of the Shuttle concept, the pre-Shuttle era should be used to demonstrate that hardware quality can be improved to the extent that system-level environmental tests no longer detect the large number of defects documented in this study. Until such a demonstration has been accomplished, no change is recommended in the GSFC policy of requiring a system-level environmental test for flight spacecraft.

CONCLUSIONS

The results of this study, in addition to the corollary studies of references 1 and 2, form the basis for the following conclusions on the space performance of GSFC spacecraft for the era of 1960 through 1970.

- The GSFC philosophy of requiring a system-level environmental test of flight spacecraft has been effective and has played a significant part in achieving a successful space record.
- Although the test practice at GSFC has been instrumental in achieving an outstanding space performance record, it has not been so conservative as to eliminate all space malfunctions.
- The time distribution of space malfunctions (and/or failures) shows that the infant mortality defects have not been completely eliminated by the test programs.
- The failures per spacecraft for system environmental tests, first day in space, first month in space, and total space life were 12, 0.9, 1.7, and 5.0, respectively.
- With present test philosophy and practice, about 35 percent of the total space malfunctions can be expected in the first 30 days in space, and about 50 percent of these will occur on the first day in space.
- If there had been no system test program conducted, the following estimated figures (based on the 57 spacecraft of this study) are considered applicable:

- a. The total space malfunctions would have quadrupled (~2000 versus 500).
- b. Approximately 75 percent (or more than 1500) of the total space malfunctions would have occurred in the first month in space.
- With present test practice, the mission-critical malfunctions (which would cause loss of 50 to 100 percent of mission objectives) were about 9 percent of total malfunctions if there had been no redundancy and about 4 percent with redundancy.
- Component malfunctions which would cause loss of 50 to 100 percent of component objectives were about 43 percent of the total malfunctions if there had been no redundancy and about 28 percent with redundancy.
- No change in GSFC test philosophy or practice is recommended until test and space performance show that additional risk is cost effective.

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